

INL/CON-08-14410
PREPRINT

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16th Pacific Basin Nuclear Conference

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October 2008

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U.S. Department of Energy
National Laboratory
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Battelle Energy Alliance



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Irradiation of the First Advanced Gas Reactor Fuel Development and Qualification Experiment in the Advanced Test Reactor

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The United States Department of Energy's Advanced Gas Reactor (AGR) Fuel Development and Qualification Program will be irradiating eight separate tri-isotopic (TRISO) particle fuel (in compact form) experiments in the Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL). These irradiations and fuel development are being accomplished to support development of the next generation reactors in the United States. The ATR has a long history of irradiation testing in support of reactor development and the INL has been designated as the United States Department of Energy's lead laboratory for nuclear energy development. These AGR fuel experiments will be irradiated over the next ten years to demonstrate and qualify new particle fuel for use in high temperature gas reactors. The experiments, which will each consist of six separate capsules, will be irradiated in an inert sweep gas atmosphere with individual on-line temperature monitoring and control for each capsule. The swept gas will also have on-line fission product monitoring to track performance of the fuel in each individual capsule during irradiation.

The design of the first experiment (designated AGR-1) was completed in 2005, and the fabrication and assembly of the test train as well as the support systems and fission product monitoring system that monitor and control the experiment during irradiation were completed in September 2006. The experiment was inserted in the ATR in December 2006, and is serving as a shakedown test of the multi-capsule experiment design that will be used in the subsequent irradiations as well as a test of the early variants of the fuel produced under this program. The experiment test train as well as the monitoring, control, and data collection systems are discussed and the status of the experiment is provided.

Keywords: *Tri-Isotopic, TRISO, Particle Fuel, Advanced Test Reactor, ATR, Advanced Gas Reactor, AGR*

1. Introduction

These irradiations and fuel development are being accomplished to support development of the next generation reactors in the United States. The AGR fuel experiments will be irradiated over the next ten years to demonstrate and qualify new particle fuel for use in high temperature gas reactors. The goals of the irradiation experiments are to provide irradiation performance data to support fuel process development, to qualify fuel for normal operating conditions, to support development and validation of fuel performance and fission product transport models and codes, and to provide irradiated fuel and materials for post irradiation examination (PIE) and safety testing.[1] The experiments, which will each consist of six separate capsules, will be irradiated in an inert sweep gas atmosphere with individual on-line temperature monitoring and control of each capsule. The swept gas will also have on-line fission product monitoring on its effluent to track performance of the fuel in each individual capsule during irradiation. The experiments are specifically designed for the irradiation position location and size, irradiation parameters (e.g. temperature, fluence, etc.) and with the umbilical tube routing necessary to connect the experiment to the monitoring, control and data collection equipment.

2. Experiment capsules

The experiment test train for AGR-1 consists of six separate stacked capsules vertically centered in the ATR core. Each capsule has its own custom blended gas supply and exhaust for independent temperature control and fission product monitoring. A capsule horizontal cross-section is shown in Figure 1 and a vertical section is shown in Figure 2. The capsules are approximately 35 mm in diameter and 150 mm in height - including the plenums between adjacent capsules. Each capsule contains 12 prototypical right circular cylinder fuel compacts nominally 12.4 mm in diameter and 25 mm long.

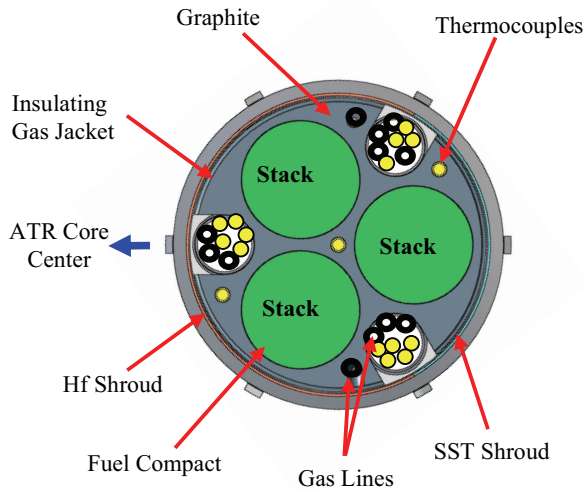


Fig. 1 AGR experiment cross-section

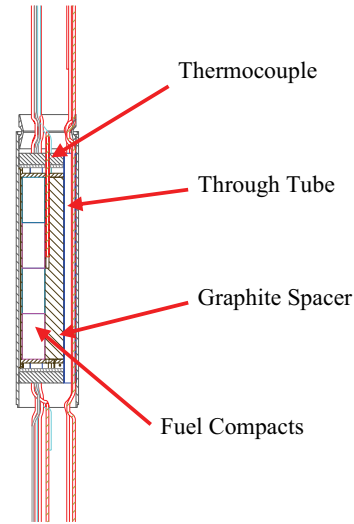


Fig. 2 AGR experiment vertical section

The fuel is comprised of 350 μm diameter Low Enriched Uranium (LEU) fuel kernels, which are covered with a layer of silicon carbide sandwiched between two pyrolytic carbon layers to make up the 780 μm nominal diameter TRISO-coated fuel particles. The fuel particles are over-coated with a thermo-set resin and pressed into fuel compacts that are then sintered to remove the volatile compounds in the resin. Each compact contains approximately 4,150 fuel particles with a mean total uranium content of approximately 0.9 grams. The experiment contains baseline fuel compacts as well as compacts made from three fuel variants with different coatings and process development variations. The compacts are arranged in four layers in each capsule with three compacts per layer nested in a triad configuration. A nuclear grade graphite spacer surrounds and separates the three fuel compact stacks in each capsule to prevent any fuel particles on adjacent compacts from touching each other, which could possibly cause a premature particle failure. Very thin (0.5 mm) graphite top and bottom end caps on the compacts prevent particle to particle contact between adjacent axial compacts. The graphite spacer also provides the inner boundary of the insulating gas jacket (approximately 0.25 mm to 1.0 mm thick depending on vertical location within the reactor core) for temperature control of the fuel during irradiation. Boron carbide was dispersed in the graphite spacer to serve as a consumable neutron poison. In addition to the boron carbide, a thin (0.25 mm thick) hafnium shield next to the outside capsule wall surrounds the two fuel compact stacks facing toward the center of the ATR core (stacks 2 and 3 shown in Figure 1). A thin (0.25 mm thick) stainless steel shield next to the outside capsule wall blankets the other fuel compact stack (stack 1 shown in Figure 1) located on the side of the capsule facing away from the ATR core to minimize the effects on the neutron flux to these already lower powered fuel compacts while retaining the same insulating gas jacket to maintain the proper irradiation temperature. The neutron poisons were necessary to limit the initial fission rate in the fuel and thereby provide a more consistent fission rate/power production during irradiation. As the boron carbide is consumed in the graphite, the fission rate in the fuel will reach a peak at about the mid-point of the irradiation and will then slowly decrease as the fuel continues to burn-up. Reducing

and controlling the initial fission rate in this manner decreased the ratio of the maximum to minimum heat generation rates in the fuel, which will allow better temperature control in the fuel during the rather long irradiation that will be in excess of two years. In addition to protecting the fuel, the graphite spacer has features machined to accommodate the thermocouples for measuring temperature within the capsule and the three through tubes containing the gas lines and thermocouples for adjacent capsules. The through tubes were positioned very precisely in the top and bottom heads of the capsules so they could also be utilized to center the graphite in the capsule and provide the necessary gas jacket for temperature control. Since the through tubes will be in contact with the high temperature graphite throughout their length, one end (the bottom) of the tubes had to be fitted with a very tight (less than 0.013 mm) slip fit between the tubes and the capsule bottom head to prevent the significant difference in (axial) thermal expansion between the capsule shell and the tubes from causing excessive stresses in the tubes. These stresses would result in bowing of the tubes, which could put stress on the graphite spacer and possibly the fuel compacts. The tight slip fit was needed to strictly limit and control any leakage of the temperature control gas between the tubes and the capsule bottom head. To prevent possible cross contamination between the capsules, a small gas flow (total of less than 20 cc/min for all capsules) is introduced into the through tubes and plenums between the capsules to ensure any leakage between the tubes and capsule heads is into the capsules, preventing flow between capsules.

There are nominally three thermocouples in each capsule (the top and bottom capsules have five and two thermocouples respectively for different reasons) located in the top, middle, and bottom areas of the graphite spacer. Since no metal could touch the fuel particles, the thermocouples measure the graphite temperature and the corresponding fuel temperatures are calculated. Flux wires were also installed in the graphite to measure both the thermal and fast neutron fluence. Since the outside diameter of the graphite establishes the inner boundary of the insulating gas jacket, it varies among the capsules depending on the neutron flux rate at the vertical location of the specific capsule within the ATR core. The boron carbide content in the graphite spacer is different in the top and bottom capsules due to the chopped cosine shaped vertical neutron profile in the ATR core.

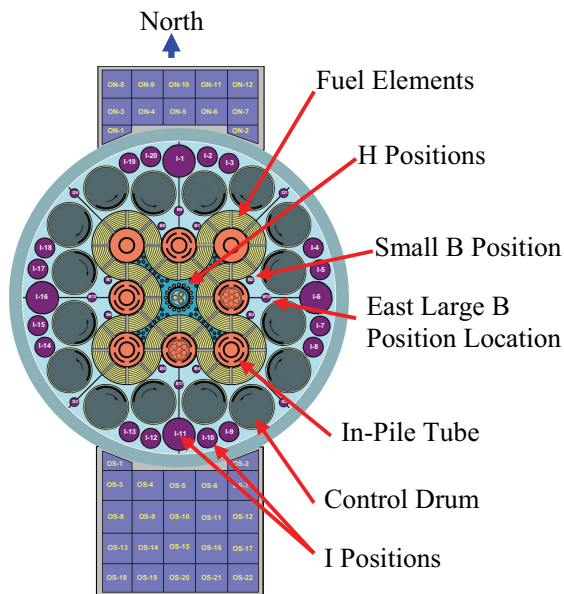


Fig. 3 ATR core cross-section

An umbilical tube (termed a lead-out) houses and protects the gas lines and thermocouple leads from the experiment capsules to the reactor vessel wall penetration. Outside the reactor vessel wall, the gas lines and thermocouple leads are connected to their facility counterparts in the temperature

monitoring, control and data collection system. The lead-out also vertically locates the experiment in the east large B irradiation position (shown in Figure 3) in the ATR core. The large B positions (38 mm diameter) were chosen for the AGR fuel irradiations due to the rate of fuel burn-up and fast neutron fluence accumulation in these positions providing an acceleration factor of between one and three times that expected in the Very High Temperature Reactor (VHTR). This acceleration factor was high enough to accomplish the irradiation within a reasonable time, but yet low enough to avoid possible premature fuel particle failures similar to those experienced in past highly accelerated particle fuel tests. In addition to limiting the acceleration factor, avoiding contact between fuel particles and limiting the materials contacting the fuel compacts/particles to only graphite and the inert temperature control gas were done to prevent possible premature fuel particle failures. The irradiation time for the AGR-1 experiment was determined by the neutron flux rate in the large B position and the Fissions per Initial Metal Atom (FIMA) average burn-up goal of 18% for all fuel compacts with a minimum of 14% for each fuel compact.[2] This requirement in combination with the slightly less than 20% fuel enrichment resulted in a rather long irradiation time, and (of course) a significantly reduced heat generation rate towards the end of the irradiation. As indicated earlier, every effort was made to flatten the heat generation rate curve as much as possible to increase the controllability of the temperatures at the end of the irradiation. This controllability was necessary to meet the time-average volume-average temperatures of $1150 \pm 30/-75$ °C for the irradiation while staying below the time-average peak temperature of 1250 °C and maximum instantaneous peak temperature of 1400 °C. These requirements provided some significant challenges in the design of the AGR-1 experiment and control systems.

3. Temperature control

Temperature control of the capsules is accomplished by adjusting the mixture ratio of two gases with differing thermal conductivities to control the heat transfer across an insulating gas jacket between the heat source (fuel fissions and gamma heating of capsule materials) and the relatively cold reactor coolant (52 °C). Helium is used as the high (thermally) conductive gas and neon is used as the insulating gas. Neon (versus argon that can provide a wider temperature control band) was selected for the insulating gas in these experiments to avoid the effects of the activated argon gas on the fission product monitors. Computer controlled mass flow controllers are used to automatically blend the gases (based upon feedback from the experiment thermocouples) to control the graphite spacer temperatures, which are analytically coupled to the fuel specimen temperatures. The gas blending system has a range of 2% to 98% of each gas (with the other gas making up the balance) allowing a very broad range of control. The gas system operates at low pressure (< 0.2 MPa) with a nominal flow rate of 30 cc/min and a maximum of 50 cc/min. With these operating conditions, very small size (1.5 mm inside diameter) stainless steel tubing was used to minimize the delivery times between the mass flow controllers and the experiment and also between the experiment and the fission product monitors to a nominal value of 2 to 2.5 minutes.

The temperature measurements are taken with the thermocouples in each experiment capsule, one of which is designated as the control thermocouple. In the event the control thermocouple fails open (as indicated by a significant increase in resistivity); the designated primary back-up thermocouple will automatically be switched to be the new control thermocouple. The thermocouples typically used at ATR are 1.6 mm sheath diameter type K, with high purity magnesia insulation. However, due to the very high thermocouple temperatures (up to 1100 °C) coupled with the relatively long irradiation; there was concern on the survivability of the thermocouples. To ensure the best survivability of the thermocouples, a selection of the most promising long life type K and type N thermocouples were purchased and tested in a thermal mock-up of the AGR irradiation conditions. In addition, several INL developmental (molybdenum-niobium) thermocouples were also included in the thermal testing to determine how they would survive the irradiation conditions.[3] The testing was conducted for four months, and based upon the test results the best performing Type N thermocouples were selected for use in the coolest positions in the capsule (away from core center) and the INL developmental thermocouples were selected for use in the hotter positions in the capsule (towards core center).

4. Fission product monitor

In order to minimize temperature changes and maintain the temperature as constant as possible, the temperature control gas system provides a continuous flow to each specimen capsule. Monitoring this continuous gas flow for fission gases can provide valuable information on the fuel performance during irradiation. The experiment flow path is shown in Figure 4.

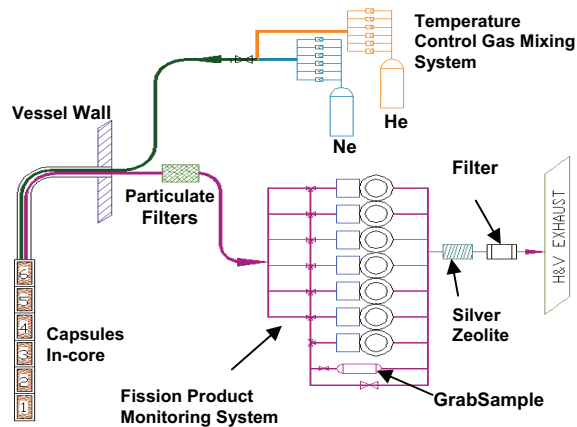


Fig. 4 AGR-1 experiment flow path

The outlet gas from each capsule is routed to individual fission product monitors, and the gas flows can be rerouted to an online spare monitor if any monitors experience detector or other failures. There is also the capability to take a grab sample of the effluent gas from each capsule. The fission product monitors consist of a spectrometer for identifying and quantifying the fission gas nuclides and a gross gamma detector to provide indication when a puff release of fission gases passes through the monitor. The gross gamma detector also provides the release timing. With the combination of a gross gamma detector and a spectrometer being continuously on-line, the gross gamma detector results can be scanned quickly to establish which portions of the voluminous spectrometer data need to be closely scrutinized. A puff release of fission gases typically indicates when a TRISO fuel coating failure may have occurred. Through identification and quantification (with uncertainties) of the isotopes, the spectrometer can be used to determine the isotopic release to birth ratio (with uncertainties) of the fission gases being detected. The determination of the release to birth ratios can establish whether a new TRISO fuel coating failure has occurred or if the fission products are merely being released from an existing failure or tramp contamination on the outside surface of the fuel particles. These details can be very important in the qualification of fuel especially in small TRISO particle fuels, where a few random particle failures are anticipated and need to be tallied very accurately to support statistical qualification of the fuel. The system was designed and response modeled to detect and quantify each individual fuel particle failure up to and including a very unlikely 250th fuel particle failure.

5. Experiment progress and status

Various tests were conducted to support the test train fabrication and assembly, including the high temperature thermocouple testing mentioned earlier and testing of the gas leakage through the very tight slip fit between the through tubes and the capsule bottom heads. Testing was also conducted on a multitude of capsule assembly processes (i.e., clearances, welding, brazing, etc.) to ensure the assembly of the test train could be accomplished as designed. Assembly of the experiment, along with the installation of the fission product monitors and the necessary modifications of the existing temperature control gas system, was completed in September 2006. The experiment was inserted in the ATR core in mid December 2006, and final flow testing of the temperature control and fission gas

monitoring system installations were performed with the experiment in the core prior to reactor start-up. Irradiation of the experiment was initiated on December 24th, and is anticipated to continue until the summer of 2009 to reach the 18% FIMA burn-up goal for the fuel compacts.

The performance and sensitivity of the fission product monitor system (FPMS) has been excellent. Very low levels of fission gases (from the anticipated very low level tramp contamination on the outside of the fuel) have been measured and recorded by the FPMS which has demonstrated both the sensitivity of the system as well as the integrity of the fuel. Testing of the transport time between the capsules and the FPMS as well as the minimum flow into the lead-out (to prevent cross flow between capsules) were conducted during the first two irradiation cycles using the capability of the FPMS to detect the short lived activated Ne-23 gas in the temperature control gas.[4] During design, the gas lines were sized to decay the activated neon but limit decay of the short lived fission gases of interest.

Initially, the design temperatures could not be achieved due to the boron content in the graphite spacer. However, as anticipated, as the boron started to burn out in the graphite, the temperatures of the fuel compacts achieved the design temperatures in all but the bottom capsule by the end of the second ATR irradiation cycle (e.g. within the first 100 days of irradiation). The bottom capsule achieved the design temperature during the fourth irradiation cycle. Approximately half of the irradiation has been completed with the experiment achieving a peak of 9% FIMA and a peak fast fluence of 1.7×10^{25} n/m² in March 2008. The fuel has performed exceptionally well with no fuel particle failures and only fission gases from tramp contamination being detected thus far. As anticipated, there have been multiple thermocouple failures (8 of 18 have failed); however temperature control has been maintained using the remaining thermocouples and the reactor physics and thermal analysis models.

6. Conclusion

Fabrication, assembly and irradiation of the experiment has provided some valuable insights and lessons learned into the design and operating characteristics of the test train as well as the temperature control and fission product monitoring systems. These insights and lessons learned can then be used to improve the experimental results and data to support qualification of particle fuel for use in high temperature gas reactors.

7. Acknowledgment

This work was supported by the United States Department of Energy (DOE) under DOE Idaho Field Office Contract Number DE-AC07-05ID14517.

References

- [1] D. A. Petti, et al, "Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program", Idaho National Laboratory Report INL/EXT-05-00465, Revision 1, August 2005.
- [2] J. T. Maki, "AGR-1 Irradiation Experiment Test Plan", Idaho National Laboratory Report INL/EXT-05-00593, August 2005
- [3] J. L. Rempe, et al, "Evaluation of specialized thermocouples for high-temperature in-pile testing", Proceedings of the International Congress on Advances in Nuclear Power Plants, Reno, NV, USA, June 4-8, 2006, Paper 6068 (2006).
- [4] S. B. Grover, D. A. Petti, "Initial irradiation of the first advanced gas reactor fuel development and qualification experiment in the Advanced Test Reactor", Proceedings of Global 2007 Advanced Nuclear Fuel Cycles and Systems, Boise, ID, USA, September 9-13, 2007, Paper 177457, (2007).